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Effect of Crystalline Anisotropy on Shock Propagation in Sapphire (Al2O3)

ABSTRACT

The main goal was to find a transparent material stronger than B4C and SiC that remains transparent under shock compression. Sapphire (Al2O3) was chosen because of its high strength and the large body of experimental data that exists to design experiments and interpret results. Published optical images of sapphire under shock indicate heterogeneous yielding and optical emission, which are probably the cause of shock-induced opacity. Heterogeneous deformation is largest for shocks traveling in the c and a directions of the hexagonal lattice; heterogeneous deformation is lower for shocks traveling in the r direction. We used c-cut, r-cut, and m-cut (basal plane) crystals for a systematic study of the mechanism that causes opacity. Shock experiments on these orientations are being performed by Gennady Kanel under a companion grant. His preliminary results suggest microstructural deformations in c-cut crystals do not occur to the same degree in r-cut. Because the least deformation appears to occur in the orientation with the lowest sound speed, we also obtained crystals with seven orientations to identify the direction with lowest sound speed, the optimal direction. These were sent to ARL for sound speed measurements. Orientations with the lowest sound speeds should be studied in future experiments.

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Final Report of STIR Grant W911NF0610517

Effect of Crystalline Anisotropy on Shock Propagation in Sapphire (Al_2O_3)

W. J. Nellis
Department of Physics
Harvard University

July 2007

Contents

Abstract

The main goal of this work is to find a transparent material stronger than B_4C and SiC that remains transparent under shock compression. Sapphire (Al_2O_3) was chosen because of its high strength and the large body of experimental data that exists to design experiments and interpret results. Published optical images of sapphire under shock indicate heterogeneous yielding and optical emission, which is probably the cause of shock-induced opacity. Heterogeneous deformation is largest for shocks traveling in the c and a directions of the hexagonal lattice; heterogeneous deformation is lower for shocks traveling in the r direction. We used c-cut, r-cut, and m-cut (a basal plane) crystals for a systematic study of the mechanism that causes opacity. Crystalline orientations were designed and purchased. Shock experiments on some of these orientations are being performed by Gennady Kanel under a companion grant. His preliminary results suggest microstructural deformations in c-cut crystals do not occur to the same degree in r-cut. Because the least deformation appears to occur in the orientation with the lowest sound speed, we also obtained crystals with seven orientations to identify the crystallographic direction with lowest sound speed, the optimal direction. These have been sent to ARL for sound speed measurements. Orientations with the lowest sound speeds should be studied in future shock experiments.

1. Introduction

A major unresolved issue in dynamic compression research is to identify an initially transparent strong dielectric crystal that remains transparent at high shock pressures. The goals of this project were to (i) find a transparent material stronger than B_4C and SiC that remains transparent under shock compression and (ii) identify the deformation mechanism by which a transparent material becomes opaque under shock. Determination of the mechanism that causes shock-induced optical opacity would facilitate choice of materials that remain transparent under shock compression.

Sapphire (Al_2O_3) was chosen for experimental investigations because of its high strength and the large body of experimental data that exists to design experiments and interpret results. Optical opacity is probably caused by light scattering caused by heterogeneous shock deformation. Sapphire has an hexagonal crystal structure and, thus, its physical properties are expected to be anisotropic. Published optical images of sapphire under shock indicate heterogeneous deformation is largest for shocks traveling in the c and a directions [1]. The c axis is normal to the basal plane, which contains the the a axis. That same set of experiments investigated samples with shock waves traveling in the r direction, which makes an angle of 57^0 with the c axis. Heterogeneous deformation was least for shocks traveling in the r direction. Velocities of sound along the c and a axes are $11.23 \pm 0.05 km/s$. Velocity of sound along the r direction is $10.47 \pm 0.05 km/s$ [2]. Thus, it appears that under shock compression heterogeneous deformation is least and optical transparency is highest in crystal directions with the lowest velocities of sound. Since in [1] only one orientation (r-cut) was studied that is not along the c direction nor in the basal plane, we undertook to determine the direction between the c and a directions expected to be the most transparent under shock compression, as well as the mechanism causing shock-induced opacity.

2. Design of experiments

Virtually all previously published experimental results on sapphire were for c-cut specimens; that is, the normal to the sample disk was parallel to the c axis. To find the orientation with the lowest velocity of sound I chose seven crystal orientations that spanned directions from parallel to perpendicular to the c axis. A key constraint on crystal orientations was commercial availability. Virtually all vendors of sapphire sell c-cut and a-cut disks for use by the electronics industry. Princeton Scientific Corp. provided the specially cut orientations needed in this study.

Hexagonal crystal orientations in this study are indicated by 4 indices, 3 in the basal plane and one along the c axis. Normally, crystal orientations are indicated by 3 Miller indices, not to be confused in this case in which 4 hexagonal indices are used. The seven orientations are listed in the Table below with the angle Θ subtended between the normal to each disk and the c axis. No previous shock experiments have been performed on d-, s-, g-, and m-cuts, nor on n-cut at the shock pressures in this study.

Table. Crystal orientations of sample disks in this study. Orientations are perpendicular to flat surfaces of disks and labeled with 4 hexagonal indices; Θ is angle between normal to each disk and c axis.

Orientation	4 indices	theta (^{0})
c-cut	(0001)	0
d-cut	$(10\bar{1}4)$	38
r-cut	$(1\bar{1}02)$	57
n-cut	$(11\bar{2}3)$	61
s-cut	$(10\bar{1}1)$	72
g-cut	$(11\bar{2}1)$	79
m-cut	$(10\bar{1}0)$	90

3. Experiments

Our initial shock experiments are designed to learn the mechanism of shock-induced opacity. Only three orientations are being used in these shock experiments. These shock experiments use c-cut for comparison with previous data, m-cut which is in the basal plane and expected to be essentially identical to any previous data for a-cut, and r-cut which is the orientation with the highest known transparency under shock. These experiments have been started by Gennady Kanel of the Russian Academy of Sciences and are funded under a companion ARO grant. Basically, a flat metal plate accelerated with explosives is impacted onto a sapphire disk that is backed with an Al foil 10 μm thick, followed by a LiF window. The particle velocity of the Al foil is measured with a VISAR. Kanel's experimental method has been described in a previous ARO report [3].

Kanel did not actually receive funding for these experiments until a few weeks ago. Nevertheless, he has performed some preliminary experiments. Waveforms of c- and r-cut samples shocked to ~30 GPa are shown in the figures below. These preliminary results for samples initially 2.4 and 5.0 mm thick show fast initial rise times that are probably elastic waves at the Hugoniot Elastic Limit (HEL). The thicker samples give more time for the leading and faster elastic wave to separate from the trailing wave. The r-cut samples appear to reach a roughly constant level of elastic compression and then the following wave has a relatively slow rise to a roughly constant level. The second wave is probably plastic deformation, though more experimental results are needed to draw firm conclusions. r-cut samples have the smallest known velocity of sound and strength in sapphire. These wave forms suggest mechanical deformation is relatively uniform and homogeneous in r-cut. The associated optical emission is also expected to be relatively homogeneous, as observed in r-cut crystals [1].

c-cut specimens behave much differently. The initial rise time is fast and indicates a higher initial HEL than for the r-cut, as expected. However, within a few ns of peak velocity, the wave forms relax to a level comparable to the first jump of the r-cuts. One preliminary interpretation of the waveforms of the stronger c-cuts is that the high initial HEL relaxes down to the HEL of the weaker r-cuts. This relaxation process might be one in which the c-cut single crystal breaks into crystallites that are trying to rotate to present the weakest crystallographic direction to the applied uniaxial shock stress. In this case crystallites would be "rubbing" on each other, producing a heterogeneous microstrutural response, localized heating, and optical emission. In other words, the shocked c-cut crystals are probably becoming opaque, as observed [1], whereas the r-cut crystals are not, at least not to the same degree. The final interpretation of these experimental records awaits completion of Kanel's systematic experimental investigation.

There might well be an orientation that is better than r-cut for retaining transparency. It is advantageous to find a relatively simple and inexpensive diagnostic to guide the search for the most desirable crystallographic orientation. For this reason, we want to measure the sound speeds of the seven above crystal orientations to see which orientation has the smallest sound speed and, thus, is most likely to be the most transparent under shock. These results will also give an estimate of how sensitive transparency under shock is to the crystallographic direction of shock propagation. Crystals of all seven orientations have recently been sent to Dr. Dattatraya Dandekar of the U.S. Army Research Laboratory. Because he was moving his office, he did not want the crystals sooner. These sound-speed results will guide choice of optimal Al_2O_3 crystal orientations to be used in future shock wave experiments.

4. Conclusions

I identified orientations of sapphire single-crystals to find the mechanism by which sapphire becomes optically opaque under shock. A total of thirty six c-cut, r-cut, and m-cut disks of various dimensions were shipped to Gennady Kanel to measure shock-wave forms with a VISAR.

Kanel’s preliminary results suggest that shock deformation in r-cut is relatively uniform and quite heterogeneous in c-cut. In r-cut the shock front travels along close to the weakest direction and in c-cut the shock front travels close to the strongest direction. The microstructural responses, observed in the VISAR records, are probably so different because the dynamic strengths of the two orientations are so different. It appears that since the strength of r-cut is probably near the minimum in crystal sapphire, crystallites formed on shock loading are stable with respect to their orientation behind the shock front. As a result, shock compression is relatively homogeneous. On the other hand, the strength of c-cut is probably near the maximum in crystal sapphire and the strength decreases rapidly with direction away from the c axis toward the r axis. It is possible, therefore, that crystallites formed on shock loading of c-cut tend to rotate so that their weakest direction is along the direction of applied uniaxial stress. This might explain mechanical relaxation of c-cut behind the shock front, observed in Kanel’s VISAR records, and the heterogeneous nature of shock-induced deformation and optical emission of c-cut observed in published optical imaging experiments.

I identified seven orientations of sapphire single-crystals to search for the weakest direction in sapphire and thus the direction most likely to remain transparent under shock compression. Velocities of sound are the inexpensive and simple diagnostic to guide this search. Crystals of all seven orientations have recently been sent to Dr. Dattatraya Dandekar of the U.S. Army Research Laboratory to measure their velocities of sound.

Future experiments should focus on determining the mechanism by which transparency is retained in shocked sapphire and, pending the outcome of the sound speed and shock measurements now in progress, VISAR measurements should be performed on crystals whose orientations are in the band in which highest optical transparency is retained under shock. That is, in addition to r-cut, other crystal orientations will be scientifically useful as well.

References

[1] D. E. Hare, N. C. Holmes, and D. J. Webb, Phys. Rev. B 66, 014108 (2002).
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[3] G. I . Kanel et al, Final Technical Report of CRDF Grant RUE2-1615-MO-06 (2007).

Figures. VISAR wave forms measured by G. Kanel in single-crystal sapphire with its c axis (labeled C below) and its r axis (labeled R below) oriented parallel to the direction of shock propagation. These velocities are the particle velocities of the interface between the sapphire sample and LiF window backing it. Thus, these velocities are those achieved on release of shocked sapphire into LiF.